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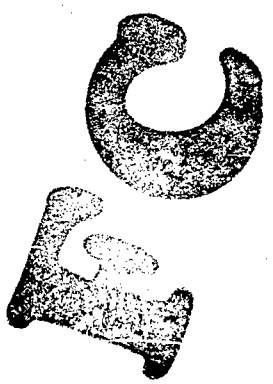
NAVORD REPORT 4383

COOK-OFF STUDIES OF THE BOOSTER XW-7 AND VARIANTS

15 OCTOBER 1957



U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

CONFIDENTIAL

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NAVORD Report 4383

COOK-OFF STUDIES OF THE BOOSTER XW-7 AND VARIANTS

Prepared by:

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ABSTRACT: XW-7 boosters were simulated, for the purposes of this study, by boosters of somewhat reduced length and with special closures, but which were made in accordance with the drawings in other respects. Boosters loaded with tetryl and with CH-6 with and without internal insulation were exposed to turbulent air at temperatures up to 500°F. Temperatures were measured at various points in the air and on the surface and in the interior of the boosters by means of thermocouples. Boosters loaded with tetryl generally "cooked-off" within a minute or two after the surface of the explosive had reached 350°F. Those loaded with CH-6 "cooked-off" in times ranging from five to forty minutes after reaching this temperature. The insulation used had a relatively small effect upon the time to "cook-off". This study was intended to and has demonstrated that the XW-7 booster will survive at 350°F for periods much longer than anticipated exposure under normal operating conditions.

A number of booster and warhead explosives were compared by means of a similar smaller scale test.

In Appendix A the theory of cook-off is discussed and calculations and experiments in continuation of this work are suggested.

NAVORD Report 4383 15 October 1957

The effect of rapid heating on the "cook-off" behavior of the XW-7 warhead booster, the "cook-off" temperatures of some new booster explosives, a comparison of the heat resistance qualtities of the explosives tetryl and CH-6 are reported. This work was authorized by task assignments NO 512-525/53019/01040 and NO 508-925/53025/01040. This work is a part of Key Problem 2.3 on guided missile research, as given by the Explosives Research Department. Other incidental information is tentative and subject to revision.

W. W. WILBOURNE

C. J. Aronson

C. J. ARONSON
By direction

CONTENTS

ILLUSTRATIONS

CONTENTS (cont'd)

COOK-OFF STUDIES OF THE BOOSTER XW-7 AND VARIANTS

INTRODUCTION

It is a fact that if an explosive charge is sufficiently heated it will explode spontaneously. This property has resulted in the notion by some observers that the "cook off" temperature of the explosive charge is a unique property of the explosive as is melting point, crystal density, or refractive index. However, this view is not supported by experiments or theory. One needs only to make a cursory search of the literature to see that the "cook-off" temperature of an explosive when heated is determined to a large degree by the shape and size of the sample, reference (a), and the techniques used in measuring the "cook-off" temperatures, references (b) through (e). In reference (b) controlled experiments were conducted with RDX and PETN 100°C above their melting points. The experimental evidence indicates that explosions due to heating arise from the thermal decomposition of the explosive, references (f) through (h). Theoretically, any one of a number of mechanisms may lead to explosion from thermal decomposition, references (a) and (b).

Since all explosives are constantly undergoing some decomposition the heating process should determine the type of cook-off reaction. When the heating process is slow causing a general temperature rise throughout the volume of the charge, the decomposition reaction is accelerated, and a runaway reaction will probably begin at some place inside the explosive charge. On the other hand, if the heating process is fast, so that a localized volume of explosive is heated to a high temperature, at some temperature and time depending on the dimension of the charge and the temperature distribution this localized volume of explosive will undergo an exothermic reaction, which will initiate surface burning or in extreme cases may cause detonation.

As pointed out above, convenient as such numbers might be to designers of explosive ordnance, "cook-off", "ignition" or "explosion temperatures" cannot be considered as fixed properties of explosive materials. The statistical distribution of thermal energy results in a finite rate of decomposition for any explosive at any temperature. If the heat liberated by this reaction is not dissipated as fast as it is liberated, "self-heating" will obviously result. A consideration of the Arrhenius equation $K = Ze^{-(E/RT)}$ will leave no room for doubt that the reaction

rate increases so much more rapidly with temperature than any heat transfer process that self heating can only result in a runaway reaction. Cook off conditions, then, are those for which heat losses cannot achieve equilibrium with heat liberated by the reaction. It is quite clear that the conditions for cook off include not only the temperature but also the size, shape, and state of aggregation of an explosive charge as well as the properties of the surroundings which affect heat transfer. It is not surprising that measured values of cook off temperatures vary widely depending upon experimental technique, apparatus, and sample size and shape, references (b) through (e).

If it is assumed that heat conduction in the solid material is the principal vehicle of heat transfer within the explosive charge the differential equation for three dimensional heat transfer may be modified to include an Arrhenius term:

$$K\nabla^2 T = \rho c \frac{dT}{dt} - \rho Q Z e^{-E/RT} \qquad (1)$$

where

ρ = density

c = specific heat

K = thermal conductivity

Q = heat of reaction

Z = frequency factor of decomposition reaction

T = absolute temperature

E = activation energy of decomposition reaction

R = gas constant

This equation has not been solved analytically but has been solved graphically and numerically for a variety of boundary conditions to obtain minimum cook off temperatures for charges of various sizes, configurations, and explosive materials. Such determinations are quite valuable aids to the understanding of the cook off process. However, their applicability to missile warhead heating problems is, at best, indirect because:

(1) The time to "cook off" at a minimum temperature is much longer than the total flight time of a missile.

(2) Equation (1) neglects phase changes, composition, and density inhomogeneities which may be important in practical cook off problems.

(3) The boundary conditions for real missile situations are much more complex than any which have been applied to equation (1) in calculations.

The relatively long cook off time at minimum temperature suggests that, for times of the order of missile flight times, most missile explosive components may be treated as semi-infinite solids, heated from a plane surface. A few rough computations supported by some of the experimental work reported herein indicate that this type of computation should give a good approximation of the space-time-temperature relationship, except near the corners for an explosive to which equation (1) is applicable. Cook, reference (e), has reduced such computations to quite workable relationships. However, in view of the fact that questions relating to the effect of phase changes, inhomogeneities, internal convection, etc., would cast doubt upon the validity of such computations, it was decided that direct experiments with boosters would give the most satisfying results.

This report is an account of some experiments designed to approximate in the most severe manner the conditions that the XW-7 warhead boosters are expected to experience when used in the 6B type TALOS missiles.

The purpose of this study was to demonstrate that the booster assembly in its present form would withstand an ambient temperature of 350°F for approximately 3.5 minutes, to study the feasibility of thermally insulating the surface of the booster explosive, and to compare the booster explosives, tetryl and CH-6*, reference (j), with reference to heat resistance.

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*CH-6 is a mixture of RDX with small amounts of several inert materials in the following ratios: RDX 97.5/Polyisobutylene 0.50/Calcium stearate 1.50/Graphite 0.5

GENERAL

It was assumed for this study that the boundary layer temperature of the missile would establish itself immediately after launching, so that the entire flight of the missile was with the safety and arming compartment at some elevated temperature. Reference (i) advises that the temperature in the vicinity of the safety and arming device, explosive lead and warhead booster for this series of missiles may reach 350 degrees Fahrenheit. In this study a reduced size XW-7 warhead booster, 3 1/2 inches in length, was placed in an insulated test chamber and hot air was blown across the surface of the booster can. The booster can was aluminum with 0.015 inch walls, and a 0.100 inch bottom. Each can was sealed by a 0.015 inch thick disc of aluminum.

EXPERIMENTAL APPARATUS AND PROCEDURE

The heat source used was a Hoskins 3.4 KW rheostat controlled electric furnace capable of a maximum temperature of 1,600°F. A coil of stainless steel tubing one-half inch inside diameter, was fitted inside the furnace. Air was blown through this tubing, and the hot air passed through an insulated pipe to the test chamber. The air entered the top of the test chamber as shown in Figure 1. The pipe leading down into the chamber stopped approximately 3 inches above the test item.

The test chamber was a steel box 11 inches wide, 14.5 inches long, and 14 inches deep. This box was lined with asbestos bricks two inches thick, leaving chamber space of 7 inches x 10 1/2 inches x 10 inches. To induce circulation ten 1/4 inch holes were drilled in the sides of the box about 3 inches from the bottom. The top of the box was covered by a dozen layers of 1/32 inch Quinorgobord* (asbestos paper) resting on the bricks that line the sides. Another layer of asbestos bricks was placed on the Quinorgobord. See Figures 1 and 2 for views of the test chamber. The test booster was supported by two wires so that the air could circulate completely around it.

The boosters used in these tests contained approximately 30 grams of explosive.** This explosive was loaded into the booster can in three

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*The trade name of an asbestos paper made by Johns-Manville Co.
**The normal XW-7 warhead booster contains approximately 80 grams of explosive.

pellets. The pellets were 1.21 inches in diameter, 0.40 inch in length, and were pressed at 15,000 psi. For test with insulation the diameter of the pellets was reduced to 1.085 inches for 1/16 of an inch of insulation, and to 0.960 inch for 1/8 of an inch of insulation. The explosives tested were tetryl and CH-6. The same explosive and inert components of the regular XW-7 booster were employed. To accommodate the reduced amount of explosive the booster can of the XW-7 was shortened. A comparisor of the "short" booster, and the XW-7 warhead booster is shown in Figure 3. After the pellets and internal thermocouples were in place the assembly was reconsolidated at 7,000 psi. Aluminum pieces, Figure 4, similar to those used in the actual booster were placed on the pellets and crimped in place. End pieces were cemented in place as employed by the XW-7 booster. The thermocouple wires came out through the hole in the front pieces, Figure 5. When insulation was used, a disc of insulation was placed on the bottom of the can, then a sleeve of insulation was slipped into the can. The pellets were inserted, and another disc of insulation was placed on top of the last pellet. Then the aluminum pieces were crimped on as before.

Five thermocouples were located in and on the test pieces. See Figures 6 and 7. The thermocouples were read by a Brown 16 point recorder reading directly in degrees centigrade. The recorder read each point once every four minutes. It was converted, by paralleling terminals, so that it read one point twice a minute and four other points each once every two minutes. The twice a minute point was always located next to the center of the second pellet. As copper leads were used with the thermocouples it was necessary to be certain that the junctions between the copper wires and the thermocouple wires were the same temperature as the instrument. If this junction temperature became higher than 35°C (95°F) an error in the indicated temperature was noted. Since the panel where the copper leads were connected to the thermocouple wires was always well insulated from the hot box by asbestos brick no error from this source was introduced.

The 16 point recorder used was not the best available instrument for this work*. The center point was recorded only twice a minute, and all

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*Two other instruments were on hand which would have been superior for the test, but the repair parts and service required to convert them to the temperature range required for this test were not available in time.

other points were recorded only once every two minutes. Fortunately, in the case of the uninsulated test pieces, the entire explosive surface was at the same temperature. There was so very little temperature drop across the aluminum can, that even the outer temperature of the can was not significantly different from the explosive surface temperature. In cases where several thermocouples located on the surface of the can and the surface of the explosive recorded almost identical temperatures, these points were plotted on a single curve and labeled "Explosive Surface".

In general not all recorded points were plotted on the graphs that follow. Where the curve was smooth only sufficient points to give the shape of the curve were plotted. However, where the curve made sudden breaks or changes all available points were plotted.

The calibration of the recorder, connected as in the actual test, was checked against boiling water, and the freezing points of tin, cadium, and potassium dichromate. The maximum error in the instrument readings was less than 3 degrees centigrade.

During the test the following procedure was followed. The furnace was turned on four (4) hours before test time, and allowed to heat up. At test time the temperature recorder was turned on, allowed to warm up, and the air blower was turned on to bring the air lines to temperature. The end of the air line was removed from the test chamber, the test booster was placed into position, and the chamber was then covered. The air blower was turned off and the air line was inserted into the test chamber. As soon as the operator reached safety, the temperature recorder* and the air blower were turned on. Time was measured from the moment the air blower was turned on. The temperature recording instrument used was an indicator as well as a recorder. In addition to the mechanism which printed the time-temperature curves a pointer moved on a scale indicating the temperature continuously. Near the end of each test this pointer was closely watched. In most cases it began to move rapidly up the scale, with an occasional pause; to record a temperature. After a few more seconds the temperature rise would suddenly exceed the capacity of the meter. The pointer then moved at full speed to the high end of the chart and began recording 1,000°C. At the same time a small "bang" was normally heard. In a short time the temperature would begin to drop, and as soon as the smoke cleared the bombproof was entered and an inspection was made of the remains.

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*The recorder was off when the thermocouple wires were connected to the instrument's lead wires.

The steel box in most cases was not destroyed. In preliminary tests with improvised charge containers that offered considerably more confinement than the XW-7 can, the chamber was always a total loss, but with the present aluminum booster cans this never occurred. The cover of the test chamber was usually still in place. The copper wire supports were usually melted where the booster had been. The thermocouple wires were also melted at the ends, and in some instances wires were fused together where they had crossed. The booster case failed as indicated in Figure 8. The ends were not blown out, instead the center was melted and burnt out. Some pieces were marked, and it was noted that the failure always occurred where the air stream struck the piece. No trace of explosive could ever be found. Tetryl left a large quantity of black soot. The CH-6 burned cleanly.

RESULTS

Figure 9 - In both of these two tests with tetryl, instruments recording the center temperatures plotted identical curves, and at the time the surface began to burn the center was still comparatively cool. The surface heated rapidly, with no break noted in the curve, and after the surface had reached 350°F its own reaction contributed heat so that the temperature climbed still faster and within a few more seconds a runaway reaction occurred.

Figure 10 shows a typical result of tetryl protected with insulation. The air was just a few degrees hotter than in the previous tests, but the rate of increase of the air temperature was almost identical in each case. There was no increase in time to cook-off. The insulation kept the explosive surface considerably cooler than the container, but it was not much below the surface temperature in the uninsulated test. Here again the center was very cool at the time the surface reaction was running away. The arrangement of the thermocouples is shown in Figure 7. Figure 11 shows a typical result of two CH-6 tests. The air temperature was over 350°F for 10 minutes before cook-off occurred. The rate of increase of the air temperature was almost the same as in the tetryl test. The explosive endured with its surface over 350°F for over 5 minutes. The break and nearly horizontal portion of the curve indicated the melting point of the RDX mixtures. In every case tested the CH-6 did not burn until its melting point had been passed. Due to the intermittent nature of the printed curve the instrument did not always note this melting break, but when it was noted it occurred at about 395°F. Shortly after the melting the heating curves indicated a surface reaction which heated the surface more rapidly, and within another minute the surface was burning. The center was well below the melting point when the reaction

began on the surface. As shown in Figure 11, tests 6 and 7 employed two different arrangements of thermocouples, but each arrangement gave the same result. This clearly indicated that the heating, and melting of the booster explosive was a surface phenomena and covered the entire surface of the booster explosive. These tests were repeated several times, the results are given in Figures 12 and 13. The air flow, in both Figures 12 and 13, started with a slightly lower temperature, approximately 250°F. However, the rise in temperature of the air, 25°F per minute, was the same in all tests. Figure 12 shows clearly the melting point of the CH-6, approximately 390°F, on the curve marked explosive surface. All tests gave the same approximate cook-off result. What seems like an unusual resistance to heat is exhibited by the explosive in tests 13 and 14, Figures 14 and 15. In the test of Figure 14 thermocouple junctions were placed next to the explosive at the ends of the booster can, and one was in contact with the can's outer surface directly under the hot air blast. The end temperatures were nearly identical, and not much below the outside temperature. This test shows that even the coolest portion of the explosive surface was at 400°F for 5 minutes before it cooked off. In this test a break was noted in the center temperature curve just before burning began on the surface. A temperature of 750°F was recorded at the center before the pellets exploded, indicating that a reaction had started at the center. In Figure 15, again the booster continued to exist over 400°F. No difference in the loading, composition, or other variables could be found to account for this superior performance. However, there seems to be some correlation between the average temperature rise per minute and the cook off time. In both cases, Figures 14 and 15, the average rate of temperature increase at the explosive surface is about 1/3 of that shown in Figures 9 and 11. This relatively slow heating of the explosive pellets, combined with a lower air temperature at the start of the test, produced what appears as increased temperature resistance for these two cases. It is of interest, however, that cook off again occurred close to the melting point of the explosive. Figure 13 shows both an increase in the surface reaction due to melting, which occurred in this case at 400°F, and an increase in the decomposition reaction near the center of the explosive, this occurring near 390°F.

Figure 16 shows the results of a test where the rate of temperature increase was made very small, approximately 10°F per minute, and the test was started with a relatively low air temperature, 200°F. The air flow was arranged so that when the temperature of the air stream reached 385°F the air stream temperature remained constant. During this test the explosive surface temperature was approaching the air stream temperature, and

reached this temperature in approximately one half hour. For the remainder of the test, some forty minutes, the air stream temperature and the surface temperature of the booster explosive were both recorded at 385°F. The center thermocouple (see Figure 7 for thermocouple arrangements of test number 9) followed and approached the temperature 385°F exponentially. After being at approximately 375°F for almost twenty minutes the center thermocouple showed a break in the heating curve, which was followed by the cook off of the explosive charge. This test supports the position, taken on tests numbers 13 and 14, Figures 14 and 15, that the apparent heat resistance of the explosive in these tests results from the low rate of increase of temperature at the explosive surface.

Figure 17 shows the result of a test that was started with the air temperature near 400°F, and the rate of air temperature increase was approximately thirty degrees per minute. The booster in this test was loaded with a thermocouple on either side of the center pellet, as shown in Figure 7, test 10. This was the latest booster tested, and no other experiments were tried with this arrangement. It is not known if the difference in temperature across the pellet is unique or common. Even on the high temperature side the center was still reasonably cool when the surface was beginning to burn. The melting point break is clearly seen in the curve showing surface temperature.

Test boosters loaded with CH-6 were also tested when insulated with 1/16 inch and 1/8 inch of Johns-Manville Quinorgobord completely covering the surface of the explosive. The cook off results obtained when 1/16 inch of insulation was used are shown in Figure 18. This test shows no improvement over the previous tests with uninsulated samples. Although the air was over 350°F for some twelve minutes it leveled off at a lower temperature than in the previous CH-6 tests. The air temperature in this test was not much different than in test 9, Figure 16, where the booster without insulation lasted approximately 70 minutes. A temperature drop of about 30°F was noted across the insulation, and due to the longer and more gradual heating the center approached the surface temperature more closely. The curves look much like those in test 13, Figure 14, where the sample was uninsulated. It is possible that a hot spot was developed at the point where the thermocouples penetrated the insulation. No thermocouple junction was located there, so the surface temperature at that point was not recorded. It is possible that without the thermocouples the insulated samples would have held up better. No surface hot spot formed when the explosive contacted the aluminum can, as the metal distributed

the heat as it was generated. If such a hot spot was developed in the insulated specimen the insulation would help retain the heat at that point so that decomposition and burning would begin there.

Figure 19 shows the results of the cook off test when 1/8 inch of Quinorgobord was used to thermally insulate the CH-6 explosive. In this test the cook off time was one minute longer than for the uninsulated booster of Figure 11. This is probably not a significant increase, since the scatter in the tests was this much. But, this test has at least one striking feature about it, that is, the break in the container surface curve near the explosive melting point. The center temperature was climbing rapidly near the end of the test. This may be due to a self heating reaction which was accelerated by the temperature increase. The last reading made by the recording instrument shows a sudden increase in temperature at the center of the charge just prior to cook off.

DISCUSSION OF RESULTS OF BOOSTER TEST

The expression "cook off temperature" means the temperature at which the explosive is either deflagrated or detonated. In every test made this explosion was preceded by a rapid deflection of the recording meter. This showed that some form of runaway reaction was taking place. In most instances it was possible to determine whether the runaway reaction was from the surface or the center of the explosive charge from the meter reading at the time of excursion of the temperature indicator. For tetryl and CH-6 it is safe to say that the cook off time was related only to the time needed to cause surface melting of the explosive charge. Even in the most severe tests the explosives withstood relatively high temperatures for a comparatively long time. But it must be remembered that resistance to high temperature is only half the problem, the other half being reliability at high temperature. The cook off temperature as it is defined here is unable to account for a decomposition rate, or the amount of decomposition prior to cook off. The decomposition products can either sensitize or desensitize the explosive. Either effect is very undesirable, as one may cause the booster to fire prematurely while the other may prevent it from firing completely. From the standpoint of reliability any rise in temperature should decrease the effectiveness of the explosive system by increasing the decomposition rate. Most explosives become insensitive when heated, reference (k). As an example of the temperature effect on the decomposition rate consider the expression for the decomposition rate as a function of temperature

$$r = Ke^{-(E/RT)} \qquad (2)$$

where r is the reaction rate,

K is a constant, temperature independent

E is the activation energy

R is the gas constant, 1.987 cal/gm mole/^{o}C

T is the absolute temperature.

E is on the order of 50,000 cals. So taking a typical case where T is 473^{o}K (as was found in this test) we have

$$r = Ke^{\frac{-50,000}{(1.987)(473)}} = Ke^{-53.2};$$

at a temperature 10^{o} higher

$$r = Ke^{\frac{-50,000}{(1.987)(483)}} = Ke^{-52.0},$$

Thus at 200^{o}C a change of only 10^{o} gives a change of 1.2 in the exponent of e which means that at the higher temperature the reaction will be 3.32 times as fast. At lower temperatures this is even more drastic. At 100^{o}C a 10^{o}C increase in temperature multiplies the reaction rate by 6.05. Thus, it is clear that although the heat resistance and sensitivity of an explosive are functions of both change in temperature due to the decomposition reaction and the rate with which the explosive is heated, very large changes in heat flow conditions are required to cause changes in cook off temperature which are of practical significance.

These tests have shown that if a localized volume or surface of explosive is heated rapidly a runaway reaction can develop from this single area. This may well be the reason why the attempts to gain additional heat resistance by insulating the explosive charge failed.

SMALL SCALE COOK-OFF TEST

The cook off test for the TALOS booster was followed by a small scale test of a number of explosives. Tests were made on pellets of various explosives, confined in brass cups to determine their cook off behavior, and to demonstrate that no size effects were introduced into the cook off temperature values assigned to the XW-7 warhead booster from measurements made on "cut down" boosters. The test charges contained 2.8 grams of explosive, approximately one-tenth of the explosive that was used in the "cut down" booster*. This explosive was formed into pellets at 2,000 psi. The pellets were one-half inch in diameter and one-fourth inch in length. Two pellets were placed into each cup, and a thermocouple junction was placed between the pellets. A second thermocouple junction was placed between the explosive and the walls of the metal cup. This completed explosive thermocouple assembly was then consolidated in the cup at 5,000 psi. The cups used had 0.030 inch thick walls, and a 0.035 inch thick brass disc was crimped over the open end of each loaded cup. At the center of each disc was a small hole that allowed for passage of the thermocouple wires.

The test samples were heated by hot air in a system similar to that described previously in this report. The results of the tests are given in Table I.

DISCUSSION OF RESULTS FOR SMALL SCALE TEST

The cook off temperature as given in Table I is the temperature at a point on the time-temperature curve where the slope showed a pronounced change in heating rate. This apparent change in heating rate was taken to mean that the decomposition reaction at this time was contributing more to the change in temperature of the explosive than was the external heat source. This change in heating rate was always followed by some form of runaway reaction. The reaction came from .1 to .3 of a minute after the change in heating rate. The cook off temperature shown in Table I is the temperature near thermocouples at either the side (S) or the center (C) of the charge at the time the runaway reaction occurs.

The results obtained with CH-6 and tetryl were not much different from the results found in the cook off tests of the "short" XW-6 warhead

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*The "cut down" booster contained more than a third of the explosive used in the regular warhead booster.

boosters. These data show that the "short" booster was near enough in size to the full size booster so that no error was introduced from this source.

Besides CH-6 and tetryl other booster explosives and a few warhead type explosives are listed in this table. It has one new booster explosive compound KHND[1], and one new explosive mixture, and from the test results both of these exhibit fair heat resistance qualities. KHND, perhaps, is not as good as is indicated by the table, since there were indications that the explosive was almost completely decomposed at the cook off temperature. For all other explosives tested, the runaway reaction caused a rapid deflection of the temperature indicator, driving the pen off scale, or at least a very large and steep temperature rise, but KHND caused only a little peak when it cooked off. In vacuum stability tests, KHND seems to become unstable near 260°C, and has detonated on some occasions when the temperature was raised to 300°C.[2] As a comparison to this HMX is almost completely unstable at these temperatures. Certainly no other explosive listed in Table I would be expected to survive a vacuum stability test at these temperatures. Normal vacuum stability tests are made at 100°C and the results for some of the explosives used in this cook off test are shown on Table I. EPM-1 is a new booster explosive mixture developed by the Explosives Properties Division of the Naval Ordnance Laboratory. It is an exact duplication of CH-6, reference (j), except that RDX has been replaced by HMX to obtain better heat resistance.

The results of the small scale cook off test clearly indicate that the rate of heating of the explosive charge is by far the most significant factor to be considered when one thinks about the cook off time for an explosive. Also, a comparison of the cook off temperature and the melting points of the booster type explosives shows that these explosives will almost always burn near their melting points. However, this may only be true for cases where the explosive is confined and the pressure developed by the decomposition reaction can not readily escape from the surface of the explosive.

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1 Potassium salt of hexanitrodiphenylamine

2 Vacuum stability data given here were obtained from Chemistry Division, NOL.

CONCLUSIONS

(a) The warhead booster assembly, XW-7, will withstand an ambient temperature of 350°F for a time greater than 3.5 minutes without cooking off. However, the problem of reliability at this temperature is still open to question.

(b) The cook-off temperature for CH-6 is significantly higher than the cook-off temperature of tetryl.

(c) No significant change in cook-off time was observed when the surfaces of CH-6 and tetryl were completely insulated by 0.125 inch of Quinorgobord.

APPENDIX A

Except for missiles which are carried externally on supersonic aircraft, all effects of aerodynamic heating result in reduced reliability or effectiveness rather than added hazard to the users since the aerodynamic heating does not occur until after the missile has been launched. This simplifies consideration of the problem since all failures from this cause whether manifested as premature explosion or dudding can be assigned the same level of seriousness.

The prediction of temperature distribution in a missile in flight is difficult, not, apparently, for the lack of understanding of either aerodynamic heating or of heat transfer, but because the analysis of transient heat flow, even in simple systems, involves differential equations with non-algebraic solutions, and in systems as complex as missile structures requires a major effort to set up for machine calculations. The problem is further complicated by the fluidity of missile designs. Changes which may be minor from a structural or mechanical standpoint can affect the heat flow situation appreciably.

In view of these difficulties in predicting the temperature distribution there is a rather natural desire on the part of those concerned with thermal problems in missiles for a table of "ignition" or "cook off" temperatures for various explosives. Although numerous tables of this kind may be found they are most notable for their lack of agreement. It is probably safe to say that none of them is very useful for predicting the effect of thermodynamic heating on the reliability of a missile warhead. The "cook-off" process itself involves heat transfer complicated by the contribution of the heat liberated by the temperature dependent reactions.

In its simplest form, based on the assumption of a single first order reaction, constant heat conductivity and capacity, a homogeneous medium, and neglecting phase changes the differential equation:

$$K\nabla^2 T = \rho c \frac{dT}{dt} - \rho Q Z e^{-E/RT} \qquad (1)$$

has received enough attention that it has become something of a classic.

This equation has been reduced to analytical form for a number of geometries, but no analytical solution of any form is known. Numerous numerical and graphical solutions have been made.

Although the solutions to equation (1) which have been made have contributed greatly to the understanding of thermal explosions, they are not specifically applicable to problems involving the aerodynamic heating of missiles because:

(1) There is room for considerable doubt regarding the validity of the assumptions upon which equation (1) is based, particularly in the range of temperatures which may be anticipated in missiles, bracketing, as it does, the melting points of the most commonly used explosives.

(2) The idealized geometries for which solutions are available are not generally very similar to missile warheads or explosive components.

(3) Most of the effort has been devoted to determining the interrelationship between dimensions, chemical kinetics, and the minimum surface temperature for thermal explosion. Such information is of little interest to those concerned with aerodynamic heating of missiles since the times associated with thermal explosions under these conditions are, in general, many times longer than the total time during which a missile is subjected to aerodynamic heating.

From rough consideration of the thermal properties of explosive materials, the dimensions of missile warheads and the flight time of missiles, it is apparent that the best simple approximation of a missile warhead charge is a semi-infinite solid.

Cook has run machine calculations on the semi-infinite solid case of equation (1) and obtained a linear relationship between temperature and the logarithm of the time interval between exposure and explosion as observed experimentally by McGill and Henkin, reference (m).

The specimen size used in the McGill-Henkin experiments is obviously too small to be considered as semi-infinite solid, except for very short time intervals. This type of linear relationship can also be expected in smaller charges, but the effects of dimensional and geometrical factors so complicate the interpretation of such data that its general application is difficult.

Machine calculations might be most useful in connection with the present problem in establishing the relationship between exposure time and the minimum size of a charge which can be considered to be a semi-infinite solid. If these calculations verify the opinion, expressed above, that this approximation may be legitimately applied to missile warheads, it should be quite easy to devise an experimental arrangement to which this approximation also applies for time-temperature cycles which bracket those experienced by missile warheads. The temperature-explosion time relationships obtained using such an arrangement could be used directly in predicting the probability of thermal premature firing of missile warheads, whether these relationships verified the simple assumptions of equation (1) or indicated that the situation is complicated by phase changes, etc. The booster sensitivities of molten TNT and many of its mixtures are appreciably less than those of the same materials in the solid state, reference (k). It is possible that phase changes, which may occur at elevated temperatures well below the melting point or those at which thermal explosions are probable, can affect the initiation sensitivity of other explosives such as tetryl or RDX. Explosive systems whose safety and reliability have been adequately demonstrated at normal atmospheric temperatures may fail at high temperatures due to such effects.

The addition of one or two per cent of a foreign material can desensitize an explosive to initiation by a factor of two or more. This susceptibility of some explosives to desensitization is a necessary factor in their applicability to ordnance. However, if the decomposition products of an explosive are effective desensitizers, an amount of decomposition which might be negligible from most points of view, could render an otherwise reliable explosive system inoperative.

Similarly the growth of detonation in primary explosives can be greatly affected by small amounts of impurities which may be decomposition products. The loss of effectiveness of detonators loaded with fulminate of mercury when stored under unfavorable conditions is probably ascribable to such effects.

Most explosive components are tested at temperatures between -65°F and 160°F to which they are subjected for extended periods. However, such tests quite obviously give no assurance regarding the reliability of the system after exposure to higher temperature, even for much shorter periods.

Data are needed regarding the sensitivity and reliability of explosive materials, components, and systems after and during exposure to all temperature-time cycles which they can survive without thermal explosions.

Although many explosives are less sensitive to boostering in the liquid state than in the solid state, some explosives are quite sensitive to mechanical blows when molten. Moreover, the melting of an explosive can make possible circumstances which are conducive to accidental explosions. If, for example, a missile is carried on the exterior of a supersonic aircraft at a speed in excess of mach 1-1.5 for a long enough period to melt the outer surface of the warhead charge, the pressure distribution along the surface, when the charge is accelerated, will be the same as if it were entirely liquid. Meanwhile the small air bubbles, which are nearly always present in cast explosives, will join to form larger bubbles. Such bubbles, adiabatically compressed by pressure changes resulting from sudden acceleration, can form reaction nuclei. Whether this sequence of events is a figment or a possible augmentation of a deck crash can be determined only by a quantitative consideration of the many factors involved.

Table I

RESULTS OF SMALL SCALE COOK-OFF TESTS

Explosive	Air Temp °F	Cook-Off Temp. °F	Time (Min.)	Melting Point °F	212°F Vacuum Stability cc/g/48 hrs., ref (1)
CH-6	445	(C) 406 (S) 385 (Center R. A.)[1]	8.3	385-395	0.10 (RDX)
Tetryl	437	(C) 240 (S) 320 (Surface R. A.)	2.0	264*	0.22
KHND**	590	(S) 625 (C) 640 (Center R. A.)	19.5	-------	----
KHND	680	(S) 617	8.5	-------	----
Composition B	555	(S) 355 (C) 392 (Surface R. A.)	2.6	-------	----
Composition B	572	(S) 392 (C) 355 (Surface R. A.)	2.8	-------	0.20
HMX	590	462***	7.8	538*	<0.1
EPM-1 (HMX/Polyisobutylene/Calcium stearate/Graphite (97.5/0.50/1.50/0.5)	482	500***	14.0	-------	----
H-6	500	(S) 385 (C) 176 (Center R. A.)	6.4	-------	0.36
HBX-3	505	(S) 428 (C) 400 (Center R. A.)	4.3	-------	0.14
RDX	478	(S) 410 (C) 392	4.0	-------	----
RDX	465	(S) 400 (C) 385 (Center R. A.)	6.1	400*	0.10
HBX-1	490	(S) 428 (C) 392	3.7	-------	0.14
Tetryl	645	(S) 320 (Surface R. A.)	0.24	264*	0.22
CH-6	590	392***	6.2	385-395	----
Tetryl	417	(S) 310 (C) 250 (Surface R. A.)	3.2	264*	0.22

*Reference (1) **KHND (Potassium hexanitrodiphenylamine - ***it was possible to distinguish center and surface temperatures.
(C) - temperature of the center of the charge.
(S) - Temperature of the surface of the charge.
(1) - Runaway reaction

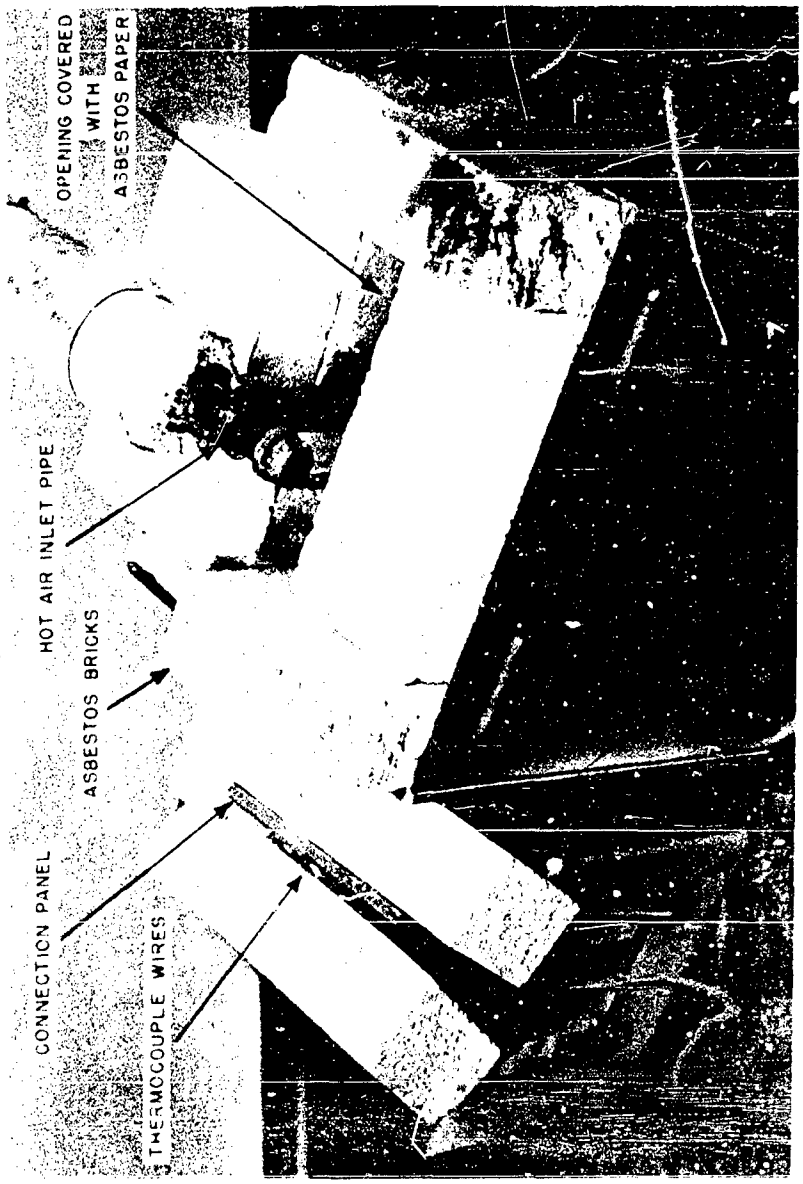


FIG. 1 TEST CHAMBER SET UP FOR EXPERIMENT

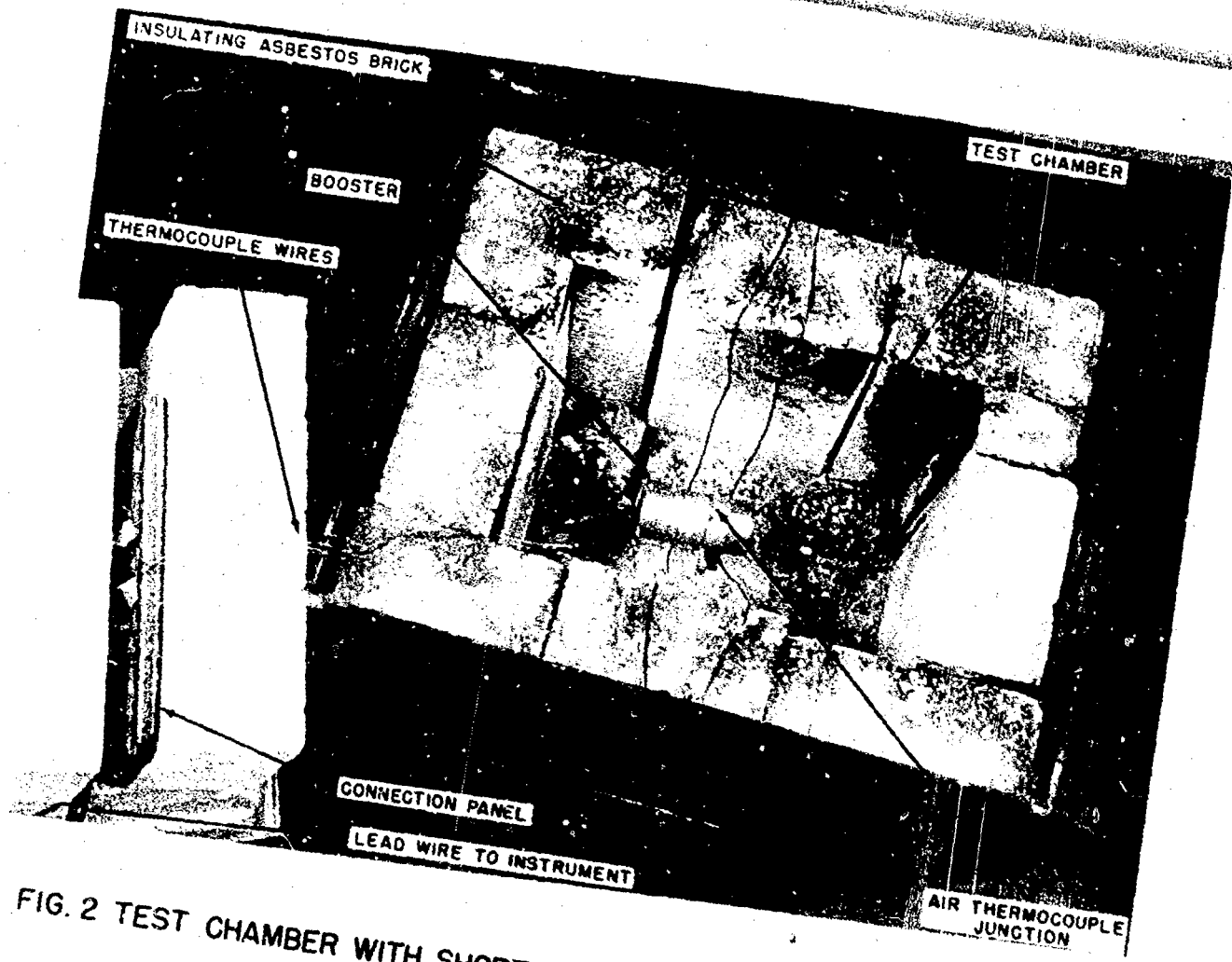


FIG. 2 TEST CHAMBER WITH SHORT BOOSTER AND ALL WIRES IN PLACE

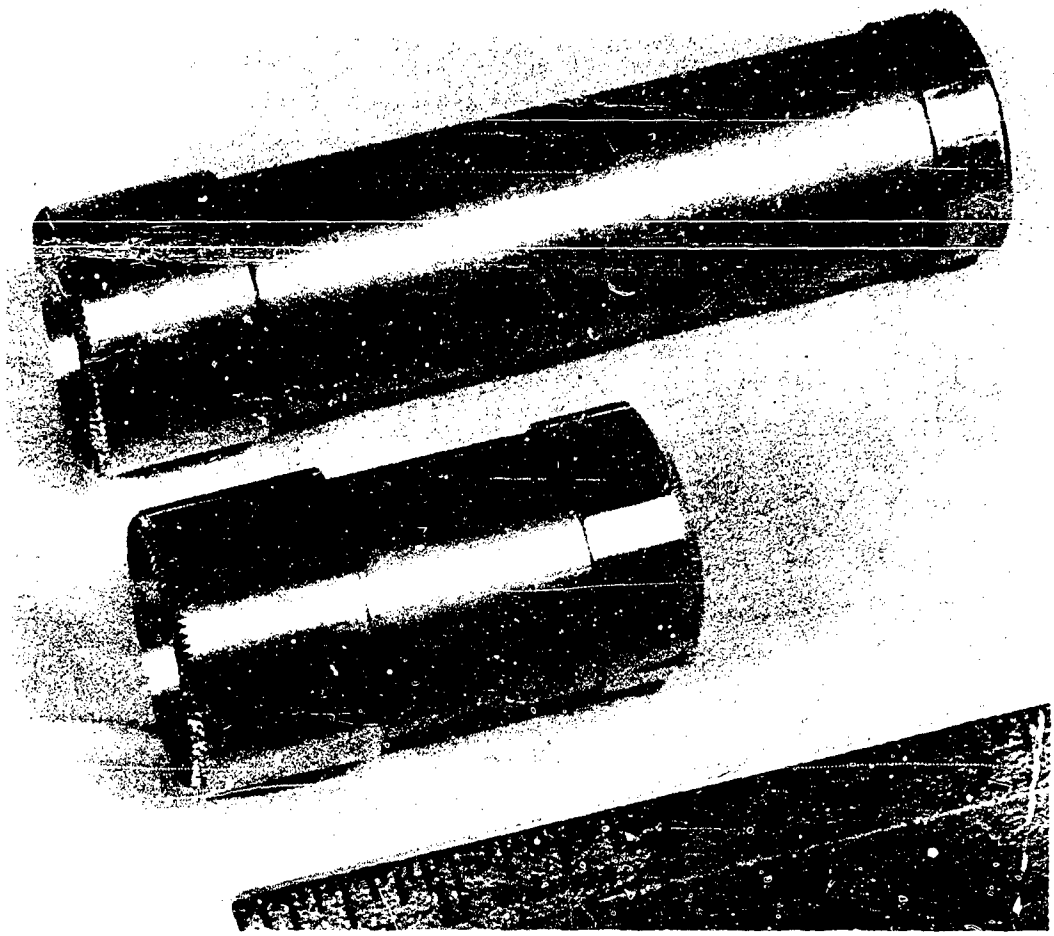


FIG. 3 COMPARISON OF SHORT AND FULL SIZE BOOSTER

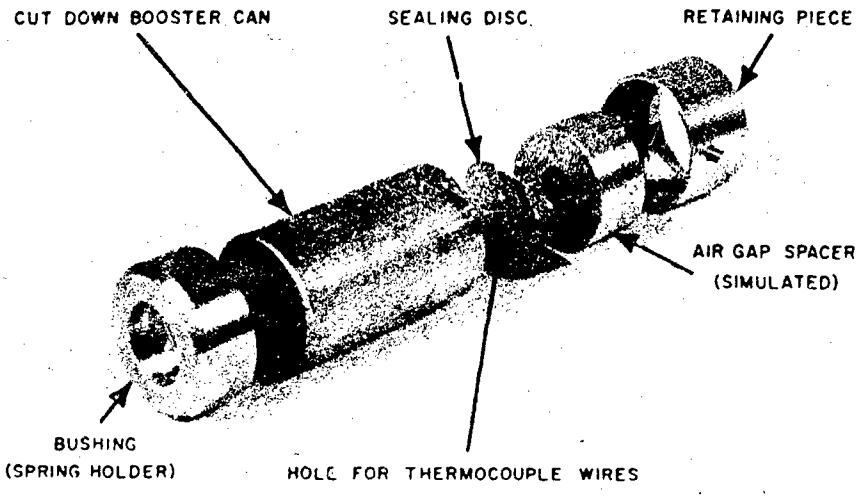


FIG. 4 EXPANDED VIEW OF BOOSTER CASE ASSEMBLY

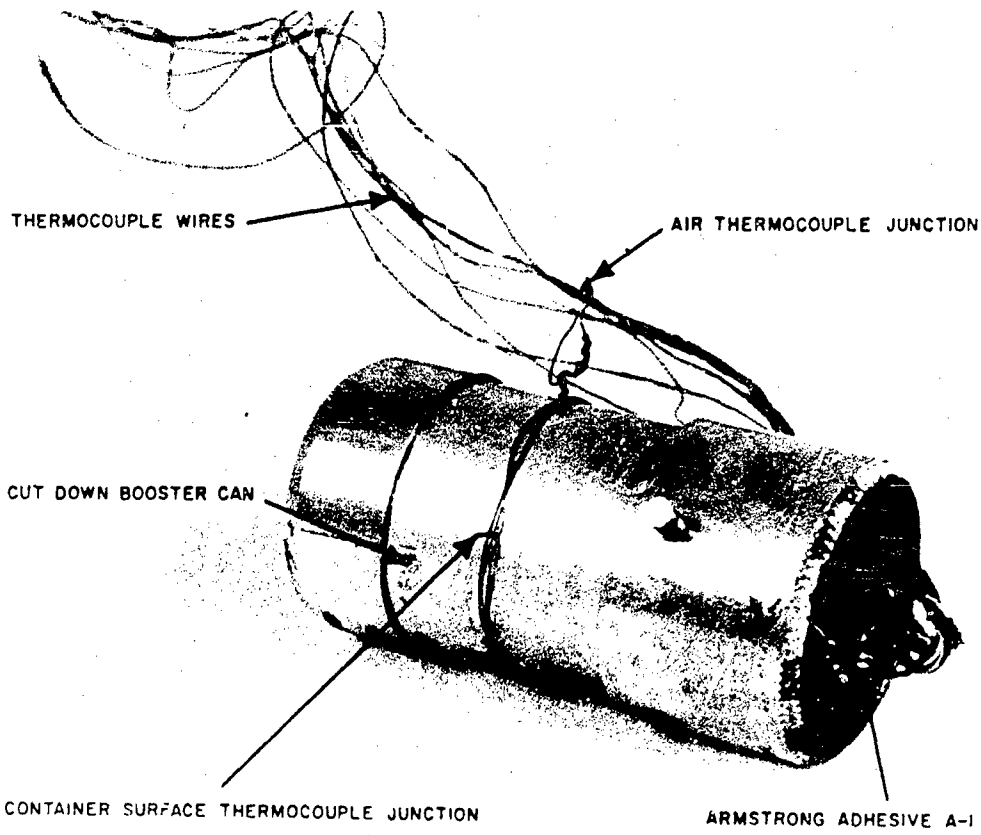
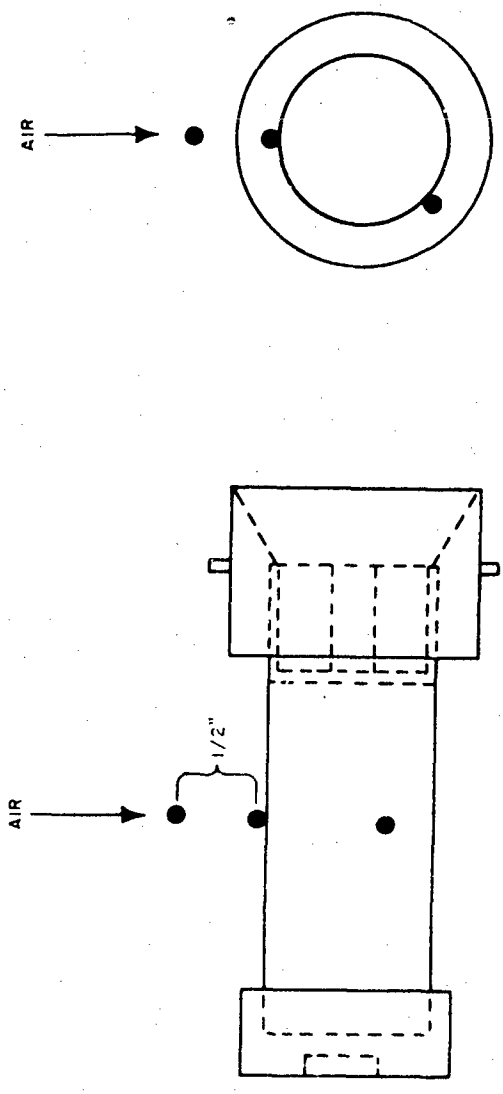


FIG. 5 LOADED SHORT BOOSTER READY FOR TEST



NOTE: WHEN THREE INTERNAL THERMOCOUPLES WERE USED ONLY ONE EXTERNAL THERMOCOUPLE WAS PLACED ON THE CONTAINER SURFACE. THE FIFTH THERMOCOUPLE WAS ALWAYS PLACED IN THE AIR STREAM.

● THERMOCOUPLE JUNCTION

FIG. 6 LOCATION OF EXTERNAL THERMOCOUPLES

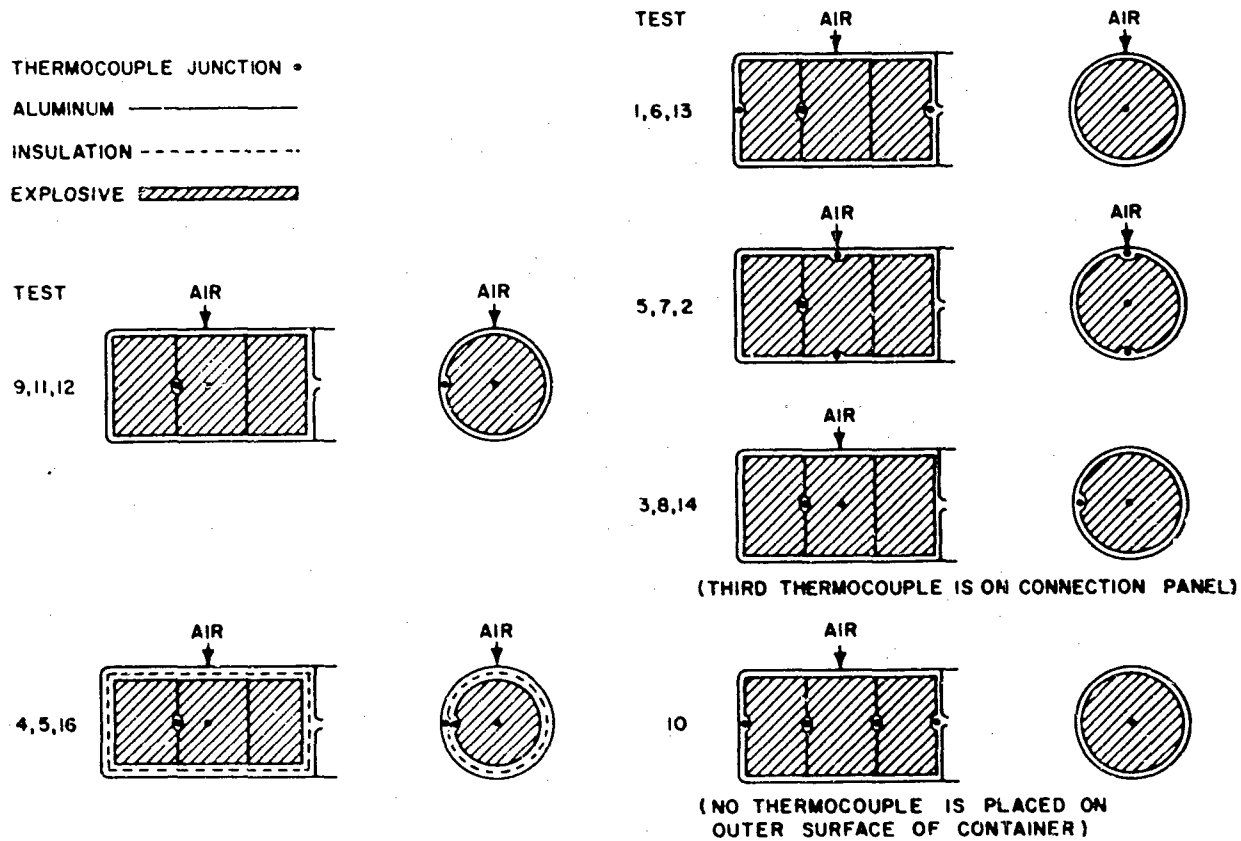


FIG. 7 LOCATION OF INTERNAL THERMOCOUPLES

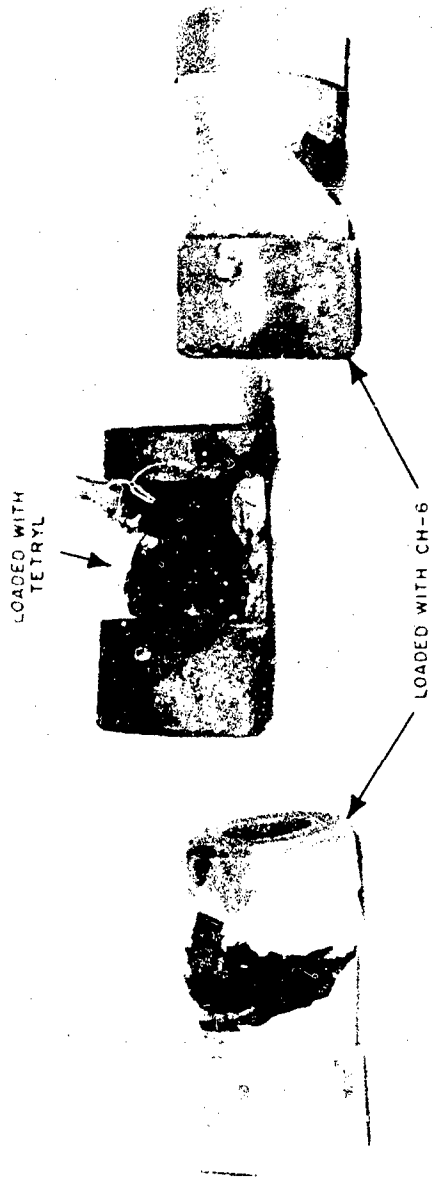


FIG. 8 TYPICAL SHORT BOOSTERS AFTER TESTING

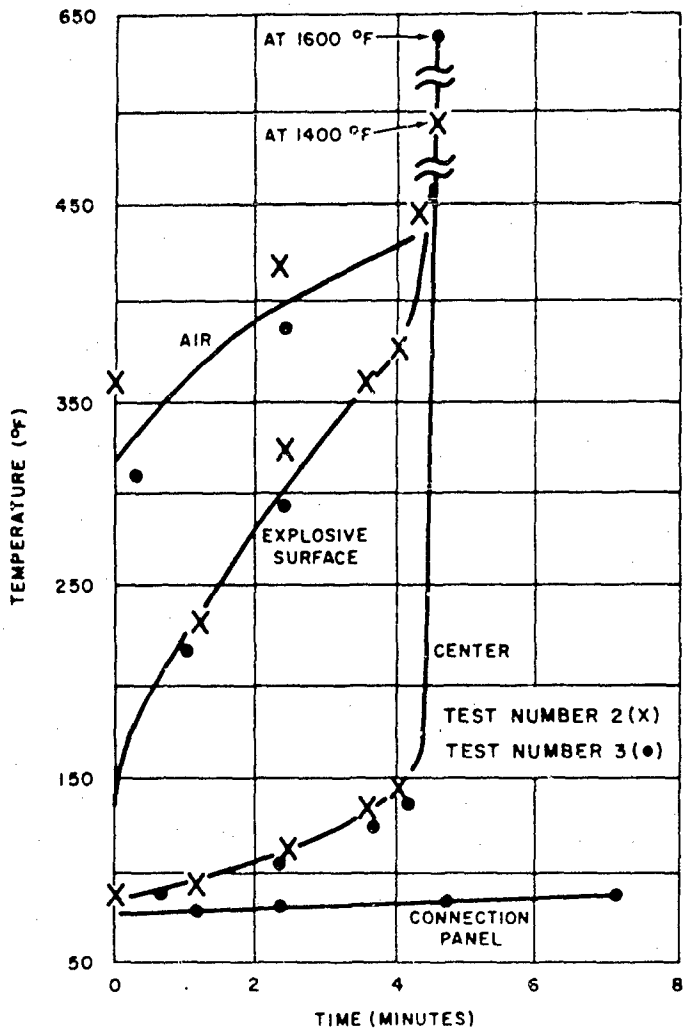


FIG. 9, TYPICAL HEATING CURVES OF UNINSULATED TETRYL PELLETS IN AN ALUMINUM CAN, THREE PELLETS 1.210" DIAMETER, 0.40" LONG

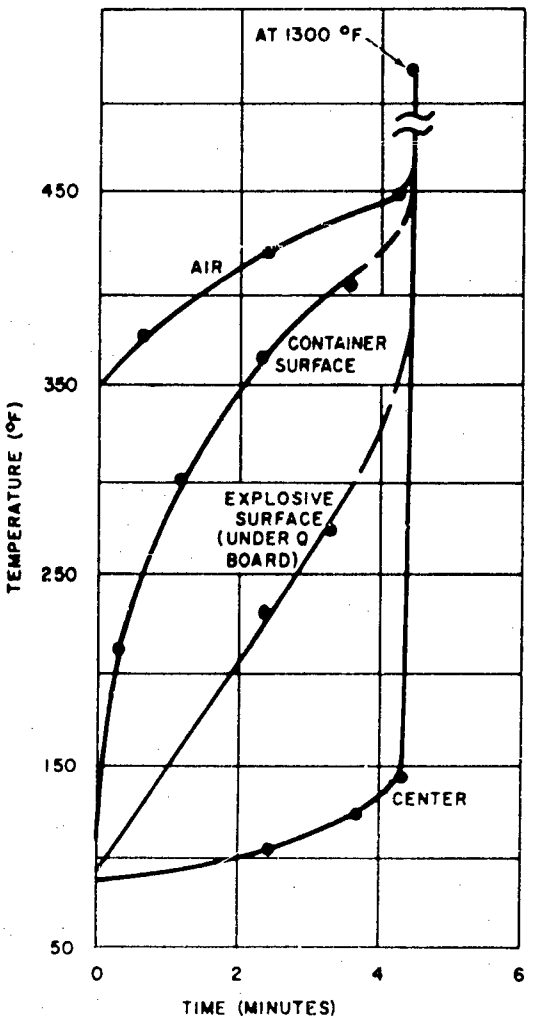


FIG. 10, TEST NUMBER 4, TYPICAL HEATING CURVES OF TETRYL PELLETS INSULATED WITH 1/16" THICK JOHNS-MANVILLE QUINORGOBORD IN AN ALUMINUM CAN, THREE PELLETS 1.085" DIAMETER, 0.40" LONG

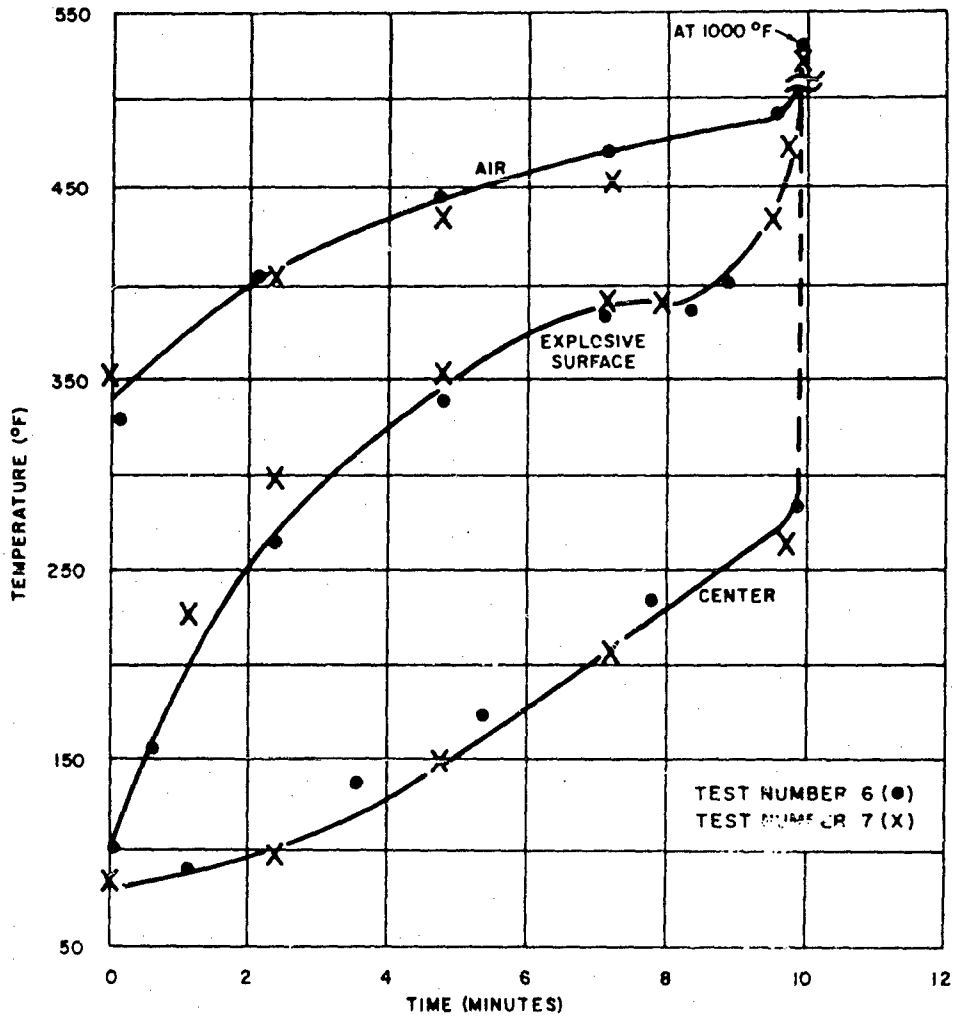


FIG. 11, TYPICAL HEATING CURVES OF UNINSULATED CH-6 PELLETS IN AN ALUMINUM CAN, THREE PELLETS 1.210" DIAMETER, 0.40" LONG

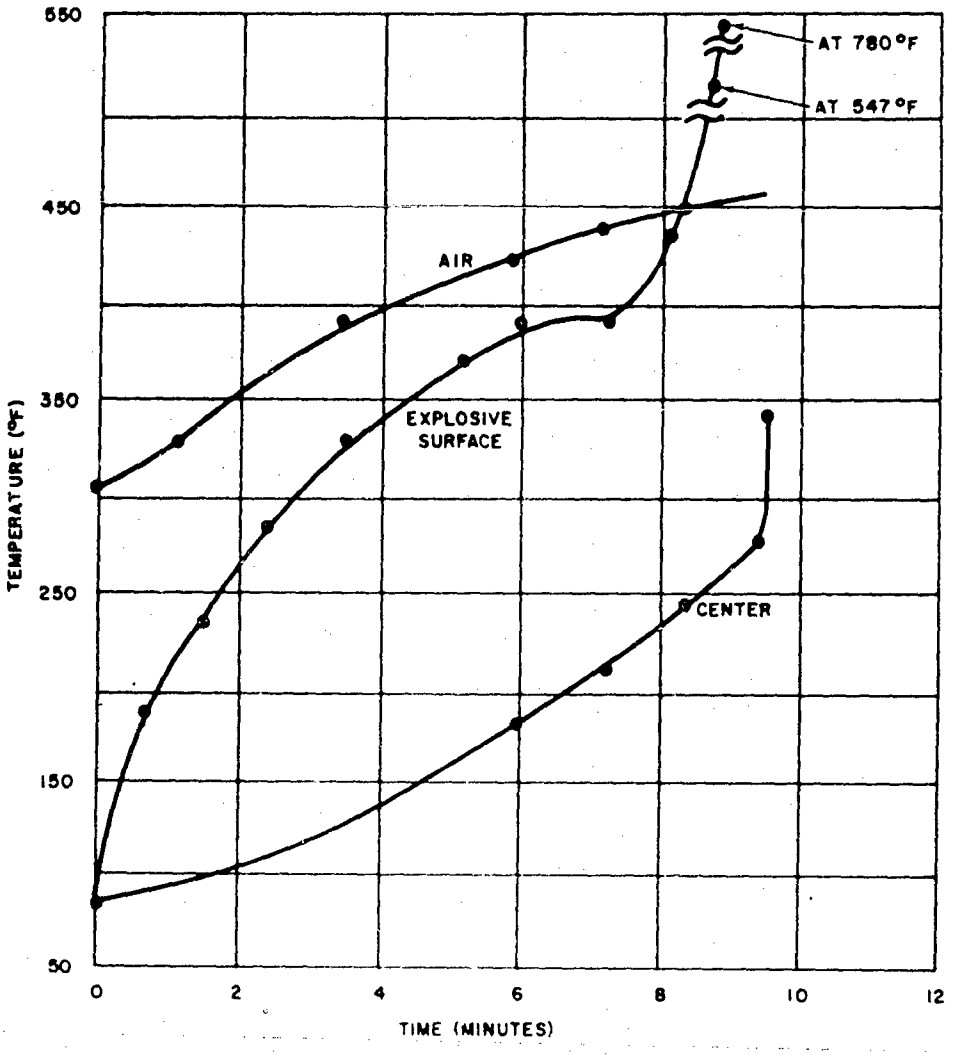


FIG. 12, TEST NUMBER 8, TYPICAL HEATING CURVES OF UNINSULATED CH-6 PELLETS IN AN ALUMINUM CAN, THREE PELLETS 1.210" DIAMETER, 0.40" LONG

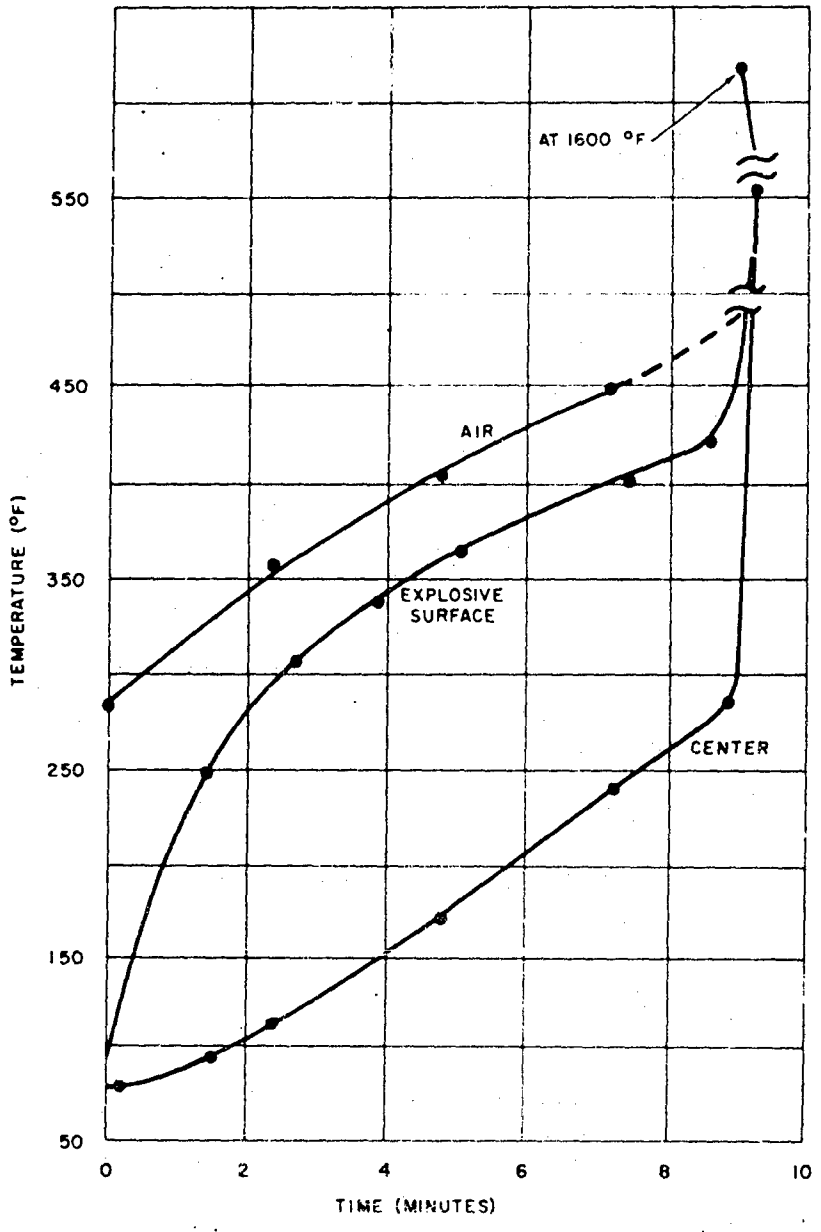


FIG. 13, TEST NUMBER 5, TYPICAL HEATING CURVES OF UNINSULATED CH-6 PELLETS IN AN ALUMINUM CAN, THREE PELLETS 1.210" DIAMETER, 0.40" LONG

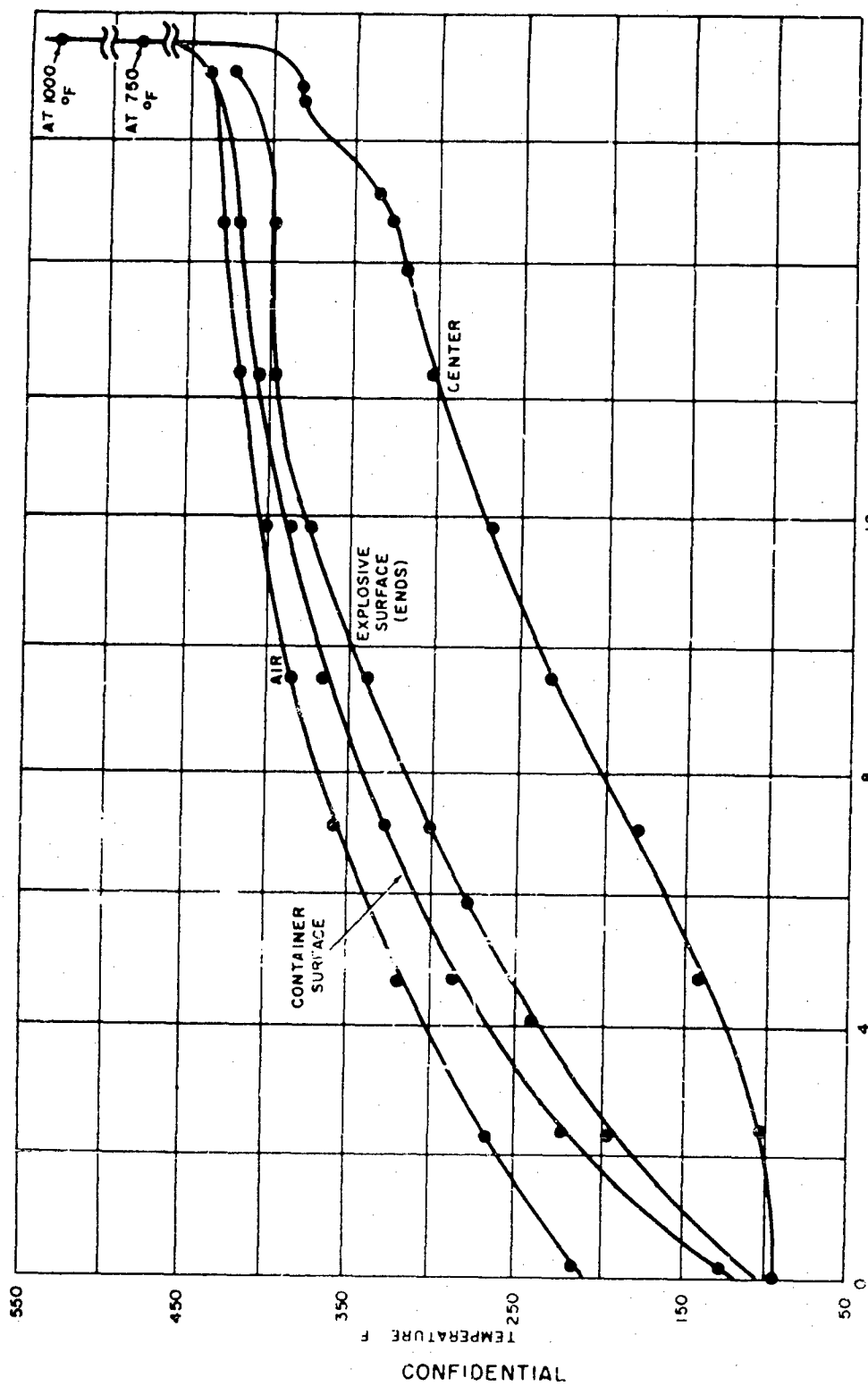


FIG. 14 TEST NUMBER 13, THERMOCOUPLE NEXT TO EXPLOSIVE AT EACH END OF ALUMINUM CAN, THREE PELLETS 1.210" DIAMETER, 0.40" LONG

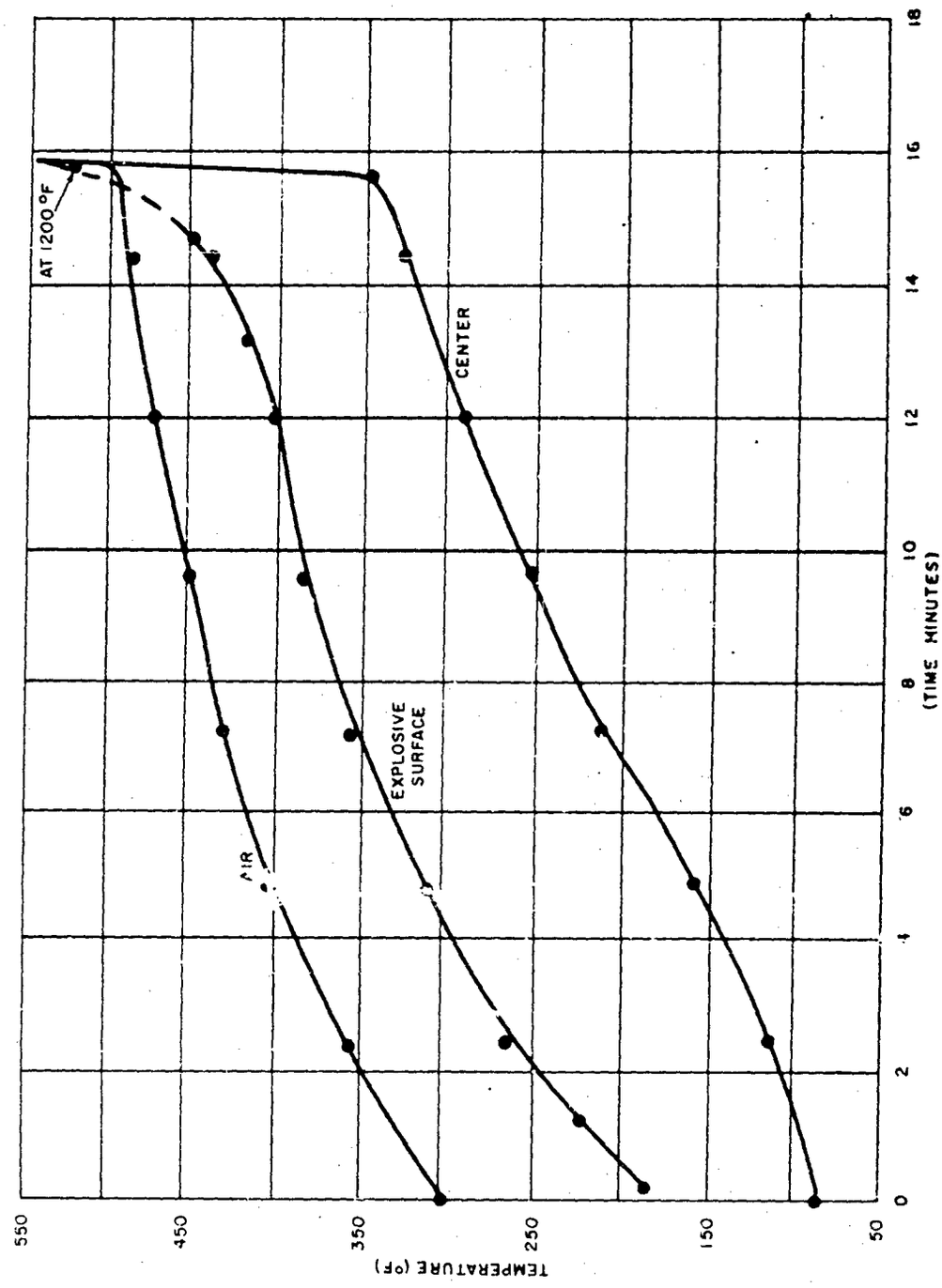


FIG. 15 TEST NUMBER 14, UNUSUAL HEAT RESISTANCE, UNINSULATED CH-6 PELLETS IN AN ALUMINUM CAN, THREE PELLETS 1.210" DIAMETER, 0.40" LONG

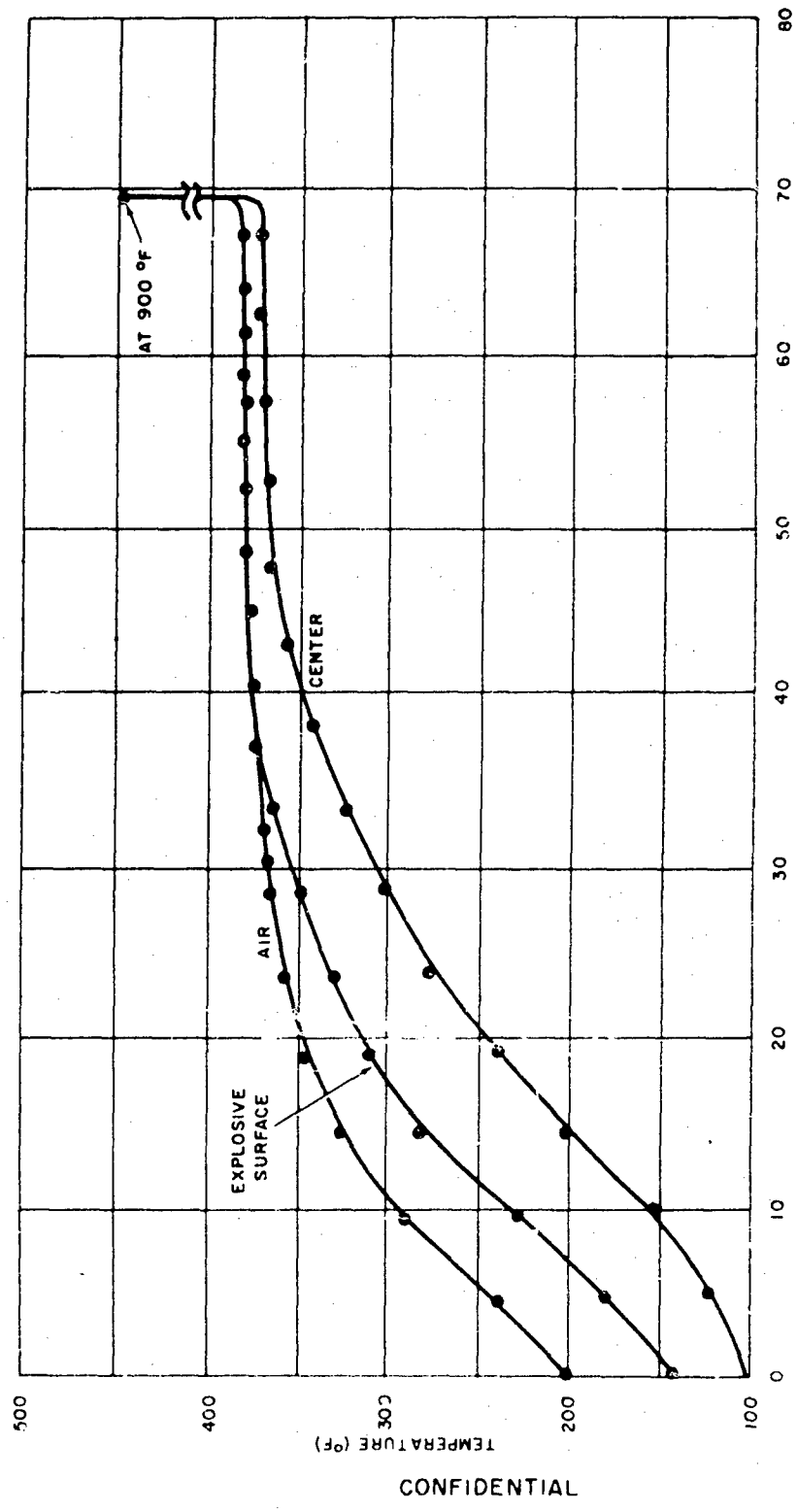


FIG. 16 TEST NUMBER 9, REDUCED AIR TEMPERATURE HEATING CURVES OF UNINSULATED CH-6 PELLETS IN AN ALUMINUM CAN, THREE PELLETS 1.210" DIAMETER, 0.40" LONG

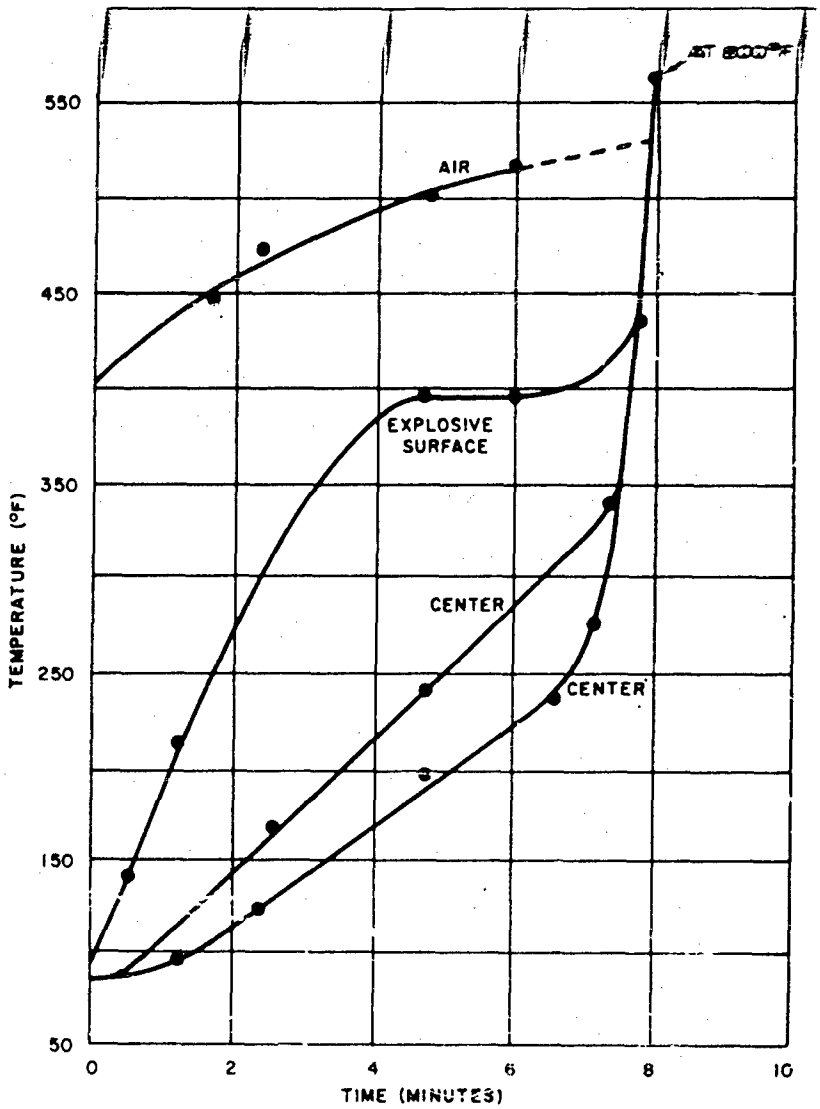


FIG. 17 TEST NUMBER 10, THERMOCOUPLE AT EACH END OF CENTER PELLET, HIGH AIR TEMPERATURE HEATING CURVES, UNINSULATED CH-6 PELLETS IN AN ALUMINUM CAN, THREE PELLETS 1.210" DIAMETER, 0.40" LONG

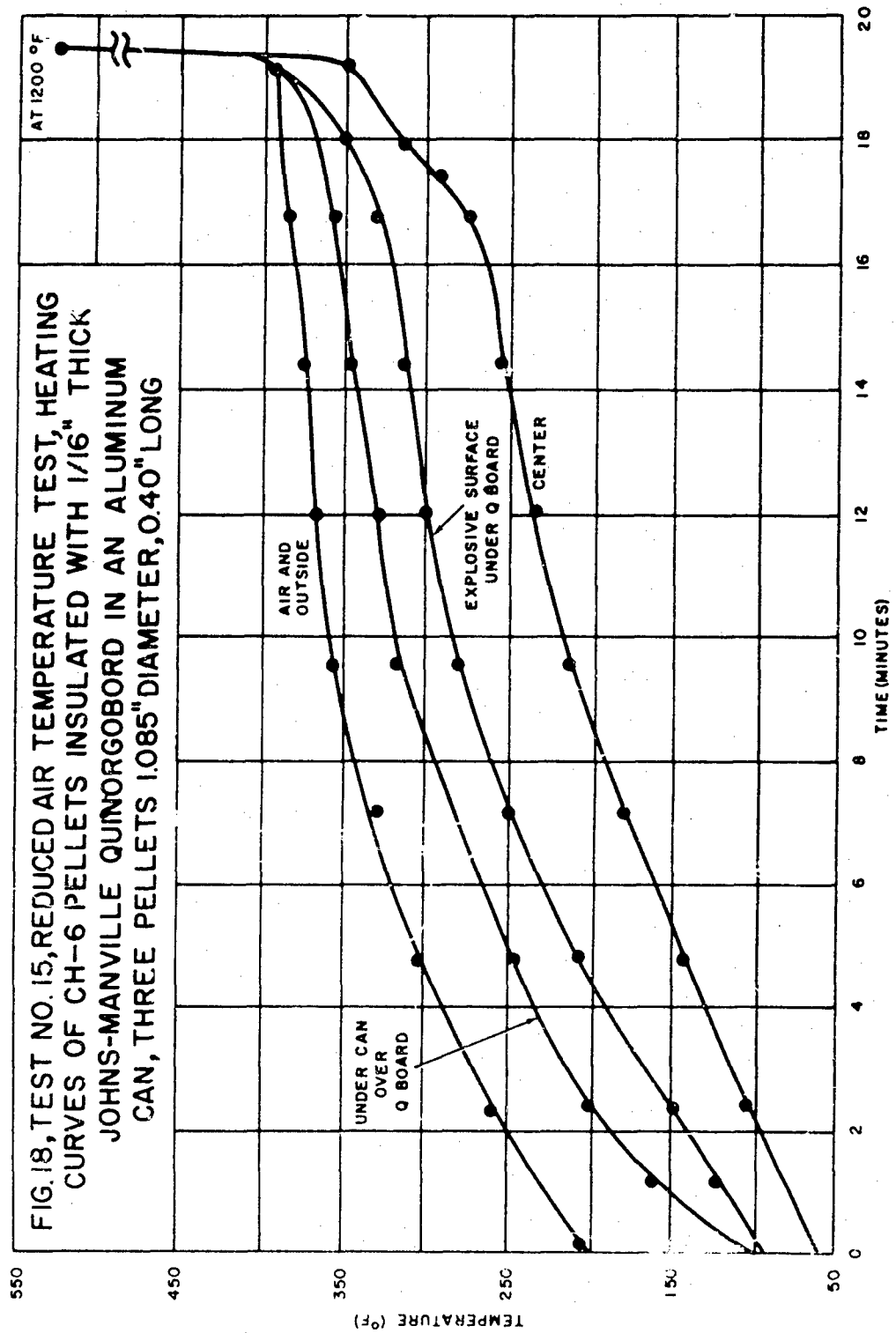


FIG. 18, TEST NO. 15, REDUCED AIR TEMPERATURE TEST, HEATING CURVES OF CH-6 PELLETS INSULATED WITH 1/16" THICK JOHNS-MANVILLE QUINORGOBORD IN AN ALUMINUM CAN, THREE PELLETS 1.085" DIAMETER, 0.40" LONG

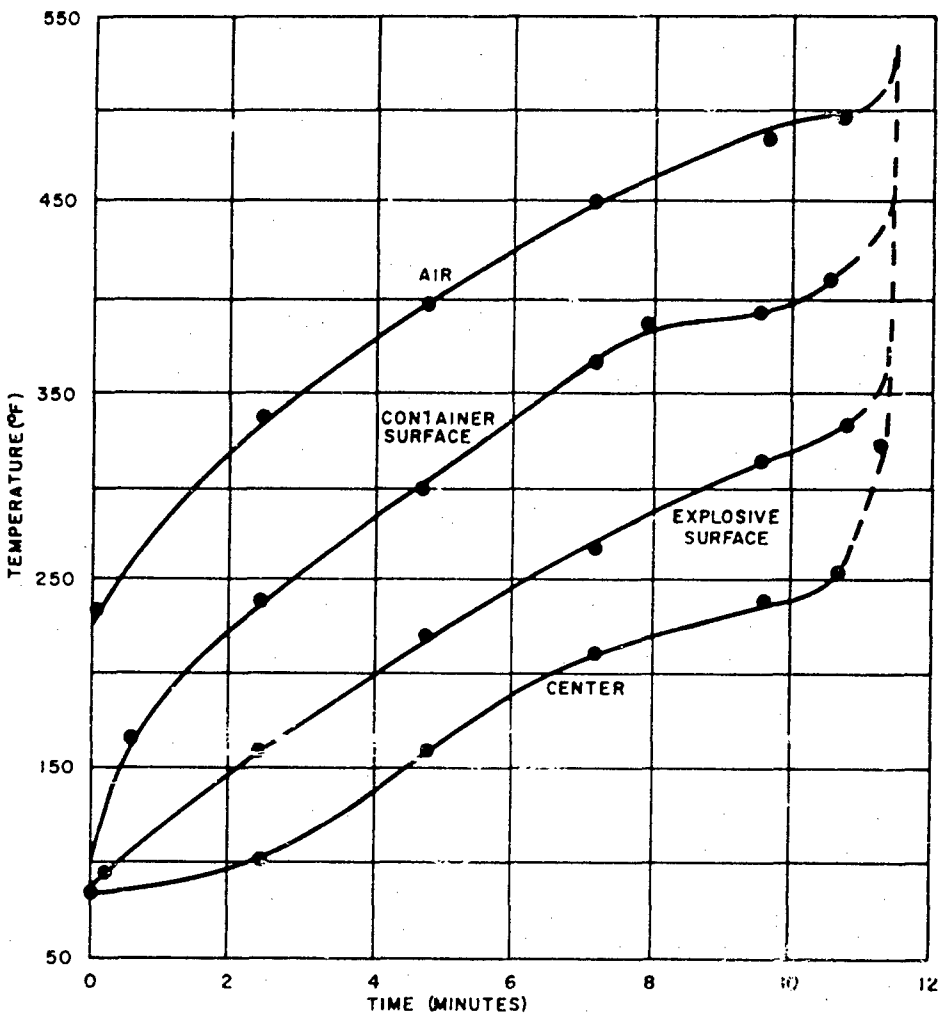


FIG. 19, TEST NUMBER 16, HEATING CURVES OF CH-6 PELLETS INSULATED WITH 1/8" THICK JOHNS-MANVILLE QUINORGOBORD IN AN ALUMINUM CAN, THREE PELLETS 0.960" DIAMETER, 0.40" LONG

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(b) AC 1908/SE 27 A. J. B. Robertson and R. P. Sinclair

(c) Properties of Explosives "Cook-Off Studies", Second Phase Report, September 1955, National Northern, West Hanover, Mass.

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(e) ARDE Report (B) 27/55, "The Theory of Thermal Explosions", October 1955, G. B. Cook

(f) AC 2025/SE32, "The Thermal Decomposition of Tetryl and RDX", C. E. H. Bawn, J. K. Hays, F. H. Pollord

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(j) NAVORD OS 7216, "Descriptions and Requirements for Pelleting RDX Composition CH-6, Bureau of Ordnance, Navy Department

(k) NOLM 10336, "The Sensitivity of High Explosives to Pure Shocks", E. H. Eyster, L. C. Smith, S. R. Walton, 16 Jul 1949

(l) NAVORD Report 2986, "Explosion Effects Data Sheets", Change 1, 14 June 1955

(m) Rates of Explosive Decomposition of Explosives. Industrial and Engineering Chemistry 44, 1391 (1952) Henkin and McGill